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14. ABSTRACT

The compressive response of many cellular materials is characterized by a sharp initial rise to a load maximum followed by an extended load plateau which terminates by a second sharp rise in load. This behavior was illustrated using aluminum and polymeric honeycombs under in-plane loads. It was shown that these characteristics are associated with inelastic buckling and a localization process in which only a narrow zone of cells experiences collapse at any given time. The collapse spreads in a steady-state fashion until all the material is affected. Models of several levels were developed and used to establish the mechanical properties of interest including the elastic modulus, the "yield" stress and the energy absorption capacity under both uniaxial and multiaxial loading conditions. The project continued with a similar investigation of open cell aluminum and polymeric foams. The mechanical response of such foams has the same general characteristics as those seen in honeycombs. The modeling of this behavior again requires proper representation of the cellular microstructure and appropriate modeling of the base material. The work on foams continues beyond d the termination of this project.

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RESPONSE AND CRUSHING OF CELLULAR SOLIDS UNDER UNIAXIAL AND MULTIAXIAL LOADINGS

Final Report for Grant No. F49620-98-0145

by
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Objectives:
Materials with cellular microstructure such as foams and honeycombs are of growing importance in the development of high performance aerospace vehicles. This is due to the benefits which result from their relatively high stiffness- and strength-to-weight ratios [1]. Advances in manufacturing processes enable the manufacture of cellular materials out of metals, polymers and ceramics to chosen densities and cell sizes. Such cellular materials are attractive for use in many applications either as primary structural materials, particularly as cores in sandwich structures, or as constituents in composites. In addition, because of their excellent energy absorbing characteristics, cellular materials are prime candidates for use in many impact mitigation applications and in packaging.

It is presently possible to tailor mechanical properties such as density, elastic modulus, crushing stress and energy absorption capacity to the needs of particular applications. For this to become fully exploitable in design, models capable of predicting these variables are an essential component. At the present, such models are at their infancy. The main thrust of this research project was first to develop through experiments the physical understanding of the mechanisms governing these properties, and second to develop micromechanical models for predicting them.

A two-prong approach was been followed in order to achieve these goals. The first involved uniaxial and biaxial in-plane crushing of hexagonal and circular cell honeycombs. The two-dimensional geometry of such honeycombs simplifies the governing mechanisms and, as a consequence, the modeling. Thus they have served as "model materials" which have helped us understand the challenges behind the mechanical behavior of cellular materials (including those of space filling foams). The second prong involved uniaxial and multiaxial crushing of metallic and polymeric open-cell foams. Following is a brief outline of the accomplishments in these two areas.

Accomplishments:

(a) Crushing of Honeycombs
The uniaxial crushing of honeycombs was investigated in earlier stages of this project [2-5]. Their responses typically exhibit an initial elastic part of relatively high stiffness which is terminated by an instability. The instability is governed by interacting geometric and material nonlinearities and results in a sharp change in the stiffness of the material coupled with localization of deformation. Under displacement controlled loading, the localized

deformation tends to spread to the rest of the material at a relatively constant load producing an extended load plateau. This load plateau is responsible for the excellent energy absorbing characteristics of these materials. When all the material is crushed, the response becomes stable and stiff again because of its densification. It has been shown that this behavior can be reproduced numerically provided the geometry of the microstructure and the nonlinearities of the base material are modeled appropriately.

Honeycomb crushing under biaxial loadings was investigated next. Experiments were conducted in the custom testing facility shown in Fig. 1. The facility was designed and fabricated for this project. The test specimen is compressed by the relative motion of four rigid blocks which surround the test section. This is achieved by employing twelve, low profile, stiff linear motion systems (slides) shown in the figures. The blocks are moved by two independent, orthogonal, hydraulic actuators run by closed-loop servo-controllers. The moving parts of the facility are mounted on a stiff frame made of structural tubing. The test specimen is in smooth contact with four lubricated platens (hardened and ground). Each axis has a load capacity of 10 kips (45 kN) and an initial gage length of 5.25 in (133 mm). All sides of the gage length can be reduced to approximately 24% of its original size. Thus, the volume of the test section can be reduced down to nearly 5.5% of its original value. Each axis can be operated under load or displacement control.

Experiments were conducted under displacement control at various velocity ratios. Figure 2a shows a sample biaxial response from a polycarbonate honeycomb with circular cells in a hexagonal packing (cell diameter 0.274 in, wall thickness 5.68×10^{-3} in and density ratio of 7%). The specimen was crushed simultaneously in the x- and y-directions at the same rate. The *true* stresses, s_x and s_y, are plotted against the respective applied displacements, δ_x and δ_y. Figure 2b shows a sequence of deformed configurations corresponding to the points identified on the responses. Initially, the material is elastic and exhibits a stiff and stable response where the cells deform essentially uniformly and the deformation of each cell is symmetric about the $x-$ and $y-$axes. The elastic regime is terminated by the onset of instability involving a mode of cell deformation which can be clearly seen in configuration ② in Fig. 2b. Continued loading results in the formation of fascinating regular patterns seen in configurations ③ to ⑥. The deformation is not uniform throughout the specimen, but a significant part of it behaves much like the cluster of cells seen in the middle of the specimen. Through this pattern, the deforming honeycomb maintains approximately hexagonal symmetry but at a different level. During the initial stages of localized crushing, the force-displacement responses monotonically decrease. Subsequently, between normalized displacements of 15-25%, they remain relatively flat and beyond 25% they monotonically increase. By the time the specimen has been crushed down to approximately 36% of its original volume ($\bar{\delta}_x = \bar{\delta}_y = 0.40$), the material has densified and both responses stiffen quite significantly. The energies absorbed at a volume change of 65% are respectively 34% and 45% higher than those measured in uniaxial crushing tests in the x- and y-directions. Fifteen biaxial experiments crushed at different rates in the x- and y-directions are reported in [6].

The biaxial crushing experiments were simulated using large scale finite element models. The models account for nonlinearities in geometry and those due to contact. The polycarbonate is modeled as an elastic-powerlaw viscoplastic solid calibrated to mechanical tests performed on polycarbonate tubes. Seven of the crushing experiments were simulated. It was not practical to model specimens the same size as those in the experiments due to computational limitations; instead, a smaller model with 10×11 cells was adopted. Through parametric studies it was demonstrated that the size of the specimen and friction between the specimen and the loading surfaces affect the initial elastic parts of the stress-displacement responses and the onset of instability. By contrast, for average crushing strains higher than approximately 10%, their effect was relatively small and the calculated responses were in good agreement with the experimental ones. As a consequence, the energy absorption capacity was predicted to good accuracy for all biaxiality ratios considered. In addition, many of the modes of cell collapse seen in the experiment are reproduced in the simulations. Figure 2a includes the calculated true stress-displacement responses for the equibiaxial test. The agreement between the experimental responses and events and the corresponding numerical ones is good. The micromechanisms of local collapse vary with the biaxiality ratio as does the energy absorption capacity. Both of these are reproduced by the model (for more details on the model and the numerical predictions see [7]).

(b) Crushing of Foams

In the latter part of the duration of the project work was expanded to include the mechanical behavior of aluminum and polymeric open cell foams. The approach followed was similar: The mechanical response to uniaxial crushing was measured for cells of different sizes. Figure 3a shows stress-displacement responses from foams of four different cell sizes spanning a range of two orders of magnitude. The basic characteristics of the responses are similar to each other. They are also similar to those of honeycombs. Figure 3b shows the microstructure of such a foam in which the polyhedral geometry of the cells is clear. It was established that to a first order approximation the microstructure scales with cell size. Microscopic observations have confirmed that localized ligament buckling and cell crushing are the main mechanisms that produce the stress plateau.

An extensive separate investigation was conducted in order to characterize the geometry of the microstructure using electron and optical microscopy and microsurgical techniques. The number of cell sides, the number of ligaments per side, the length of the ligaments and their cross sectional characteristics including variation along the length have been established statistically for one of the foams. These characteristics were subsequently used to generate idealized but also representative polyhedra which yield the correct density ratio and the correct linearly elastic and "inelastic" properties.

A third task involved the measurement of the mechanical properties of the base materials. Polymer chemists have postulated that the foaming process produces ligaments with unique mechanical properties not obtainable in bulk material. Thus, we developed a uniaxial testing fixture capable of testing individual ligaments extracted from the cells. The microtester is sensitive down to a load level of 10 gm. The polyurethane material was found to have rubber like behavior and to be quite rate dependent.

Modeling was conducted at different levels. Close form strength of materials solutions have been developed for the elastic properties. The onset of instability was investigated through characteristic cell FE models. Large scale micromechanical FE models with many cells, representative of those seen in the actual foams, were developed. In addition to producing the modulus and "yield stress," such models can also predict the crushing stress and energy absorption capacity.

The investigation of the mechanical behavior of foams was at its early stages at the termination of this project. Work continued with support from other sources and resulted in two excellent publications produced in 2003.

References:

1. Gibson, L.J. and Ashby, M.F., *Cellular Solids: Structure and Properties*-2nd Edition, Cambridge University Press, 1997.
2. Papka, S.D. and Kyriakides, S., "In-plane Compressive Response and Crushing of Honeycomb." *Journal of the Mechanics and Physics of Solids* **41**, 571-592, 1994.
3. Papka, S.D. and Kyriakides, S., "Experiments and Full-Scale Numerical Simulations of In-Plane Crushing of a Honeycomb." *Acta Materialia* **46**:8, 2765-2776, 1998
4. Papka, S.D. and Kyriakides, S., "In-plane Crushing of a Polycarbonate Honeycomb." *Int'l Journal of Solids & Structures* **35**, 239-267, 1998.
5. Papka, S. D. and Kyriakides, S., "In-plane Crushing of a Polycarbonate Honeycomb." In, Proceedings IUTAM Symposium *Material Instabilities in Solids*, June 1997, Delft, Ed. R. de Borst and E. van der Giessen, Wiley, 1998, pp. 159-183.
6. Papka, S.D. and Kyriakides, S., "In-Plane Biaxial Crushing of Honeycombs: Part I Experiments." *Int'l Journal of Solids & Structures* **36**:29, 4367-4396, 1999.
7. Papka, S.D. and Kyriakides, S., "In-Plane Biaxial Crushing of Honeycombs: Part II Analysis." *Int'l Journal of Solids & Structures* **36**:29, 4397-4423, 1999.

Personnel Supported:

Scott D. Papka, Ph.D. sudent, Graduated in May 1998
Rob Green, M.S. student, Graduated in May 2000
Lixin Gong, Ph.D student, Continues studies

Publications

1. Papka, S.D. and Kyriakides, S., "In-Plane Biaxial Crushing of Honeycombs: Part I Experiments." *Int'l Journal of Solids & Structures* **36**:29, 4367-4396, 1999.
2. Papka, S.D. and Kyriakides, S., "In-Plane Biaxial Crushing of Honeycombs: Part II Analysis." *Int'l Journal of Solids & Structures* **36**:29, 4397-4423, 1999.
3. Papka, S.D. and Kyriakides, S., "Experiments and Full-Scale Numerical Simulations of In-Plane Crushing of a Honeycomb." *Acta Materialia* **46**:8, 2765-2776, 1998.
4. Papka, S.D. and Kyriakides, S., "In-plane Crushing of a Polycarbonate Honeycomb." *Int'l Journal of Solids & Structures* **35**, 239-267, 1998.

5. Papka, S. D. and Kyriakides, S., "In-plane Crushing of a Polycarbonate Honeycomb." In, Proceedings IUTAM Symposium *Material Instabilities in Solids*, June 1997, Delft, Ed. R. de Borst and E. van der Giessen, Wiley, 1998, pp. 159-183.

Keynote Presentations

Kyriakides, S. and Papka, S.D., "In-Plane Crushing of Honeycombs." 20th Int'l Congress of Theoretical and Applied Mechanics, Chicago, IL, August 27-September 2, 2000 (Keynote Talk).

Patents:
None

Honors/Awards:
- Kyriakides, S. Elected Fellow of the American Academy of Mechanics, Spring 2000
- Kyriakides, S. New Endowed Professorship: Temple Foundation Endowed Professorship No. 1 UT-Austin (9/ 1999)

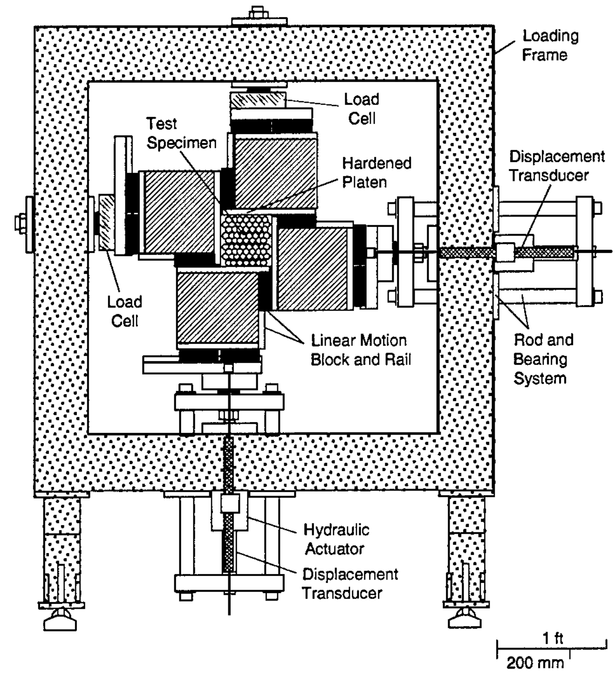

Fig. 1a Scaled drawing of biaxial crushing machine

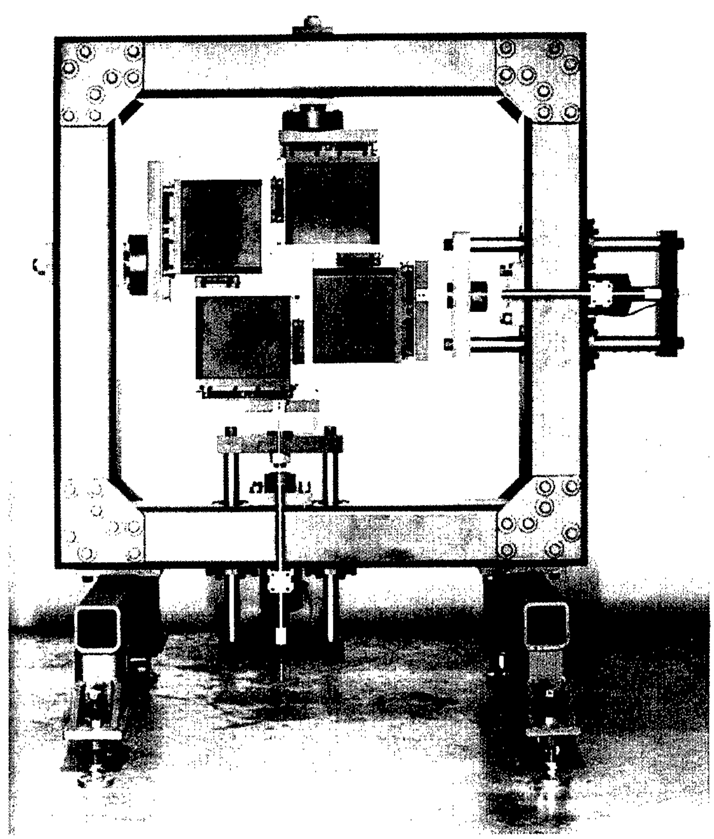

Fig. 1b Photograph of biaxial crushing machine

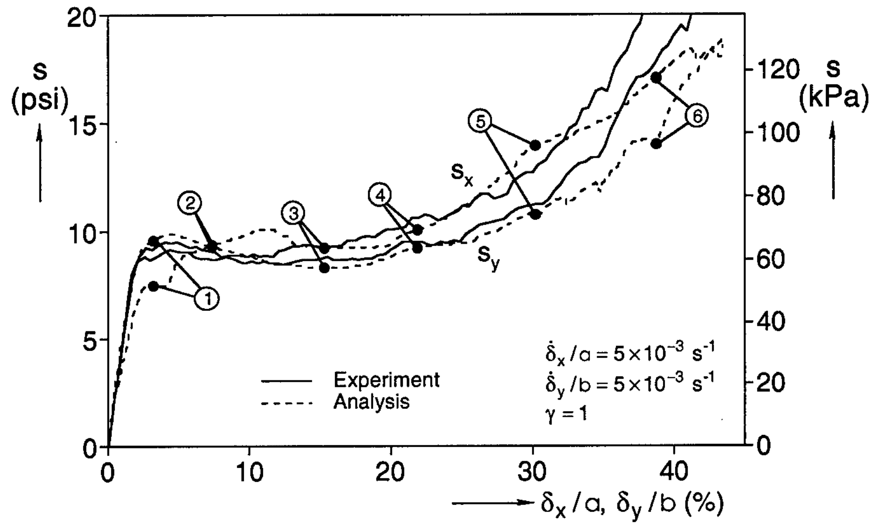

Fig. 2a Measured and calculated true stress-displacement responses for equibiaxial crushing

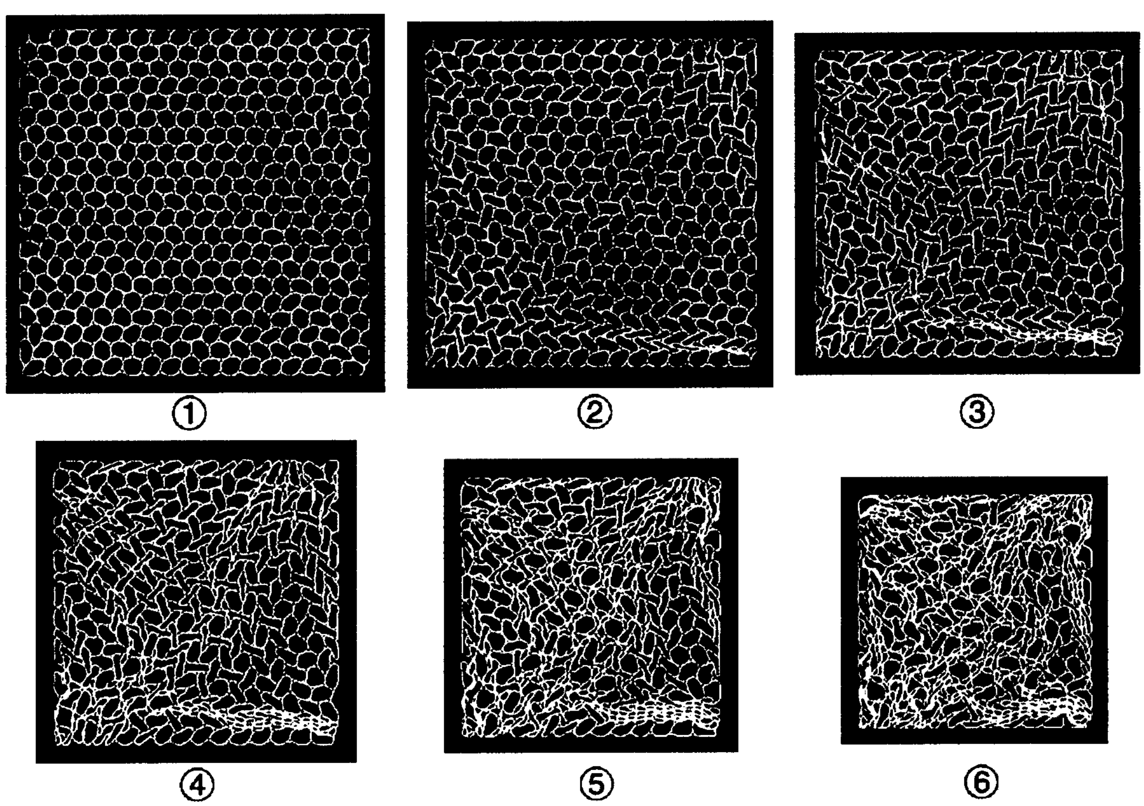

Fig. 2b Sequence of honeycomb deformed configurations corresponding to responses in Fig. 2a

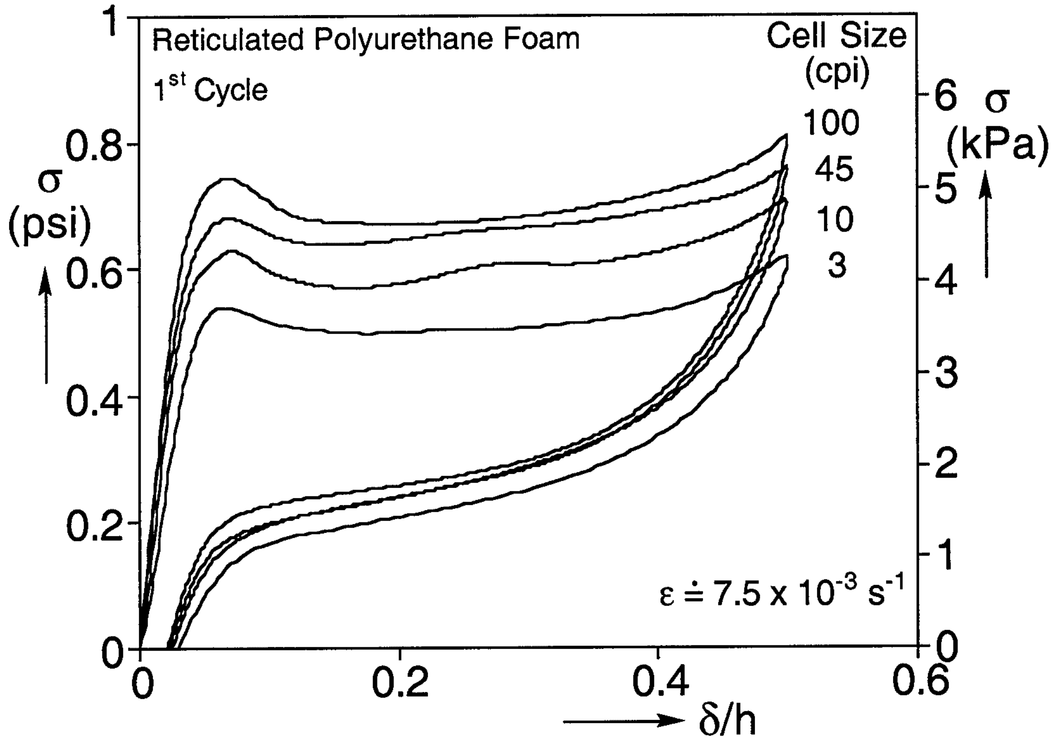

Fig. 3a Stress-displacement responses of polyurethane foams for various cell sizes

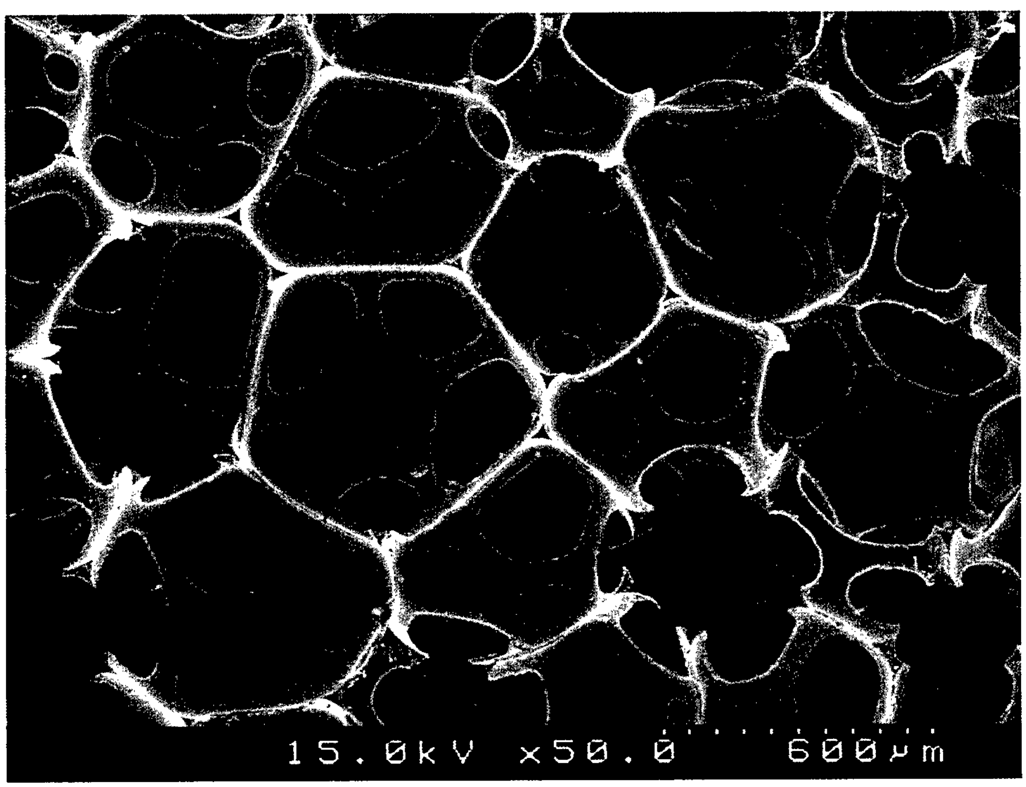

Fig. 3b Micrograph showing cell microstructure for an 100 cells per inch foam